

The ejection of T Tauri stars from molecular clouds and the fate of circumstellar discs

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ABSTRACT

We investigate the evolution of circumstellar discs around T Tauri stars that are ejected from small stellar clusters within molecular clouds. In particular, we study how the interaction that leads to ejection may hasten the transition between Classical and Weak-lined T Tauri status. In our models, ejections of T Tauri stars at velocities of 3–10 km/s truncate the accretion disc at radii between 1 and 10 a.u., reducing the viscous evolution time of the disc so that accretion rapidly ceases. The observational appearance of the resulting systems is then dependent on the presence or absence of a stellar magnetic field. For non-magnetic stars we find that a near-infrared excess should persist due to reprocessing of stellar radiation, but that this is greatly diminished for magnetic T Tauri stars by the presence of a magnetosphere extending to corotation. In either case, there is a period when ejected stars should appear as non-accreting systems with detectable circumstellar material at wavelengths of 5 microns and beyond. We discuss the implications of these results for models in which ejected stars contribute to the halo of pre-main-sequence objects discovered from ROSAT observations of star forming regions and the All-Sky Survey.

Key words:

stars: pre-main-sequence – stars: magnetic – accretion discs – X-rays: general

1 INTRODUCTION

The ROSAT All-Sky Survey (RASS) has identified large numbers of candidate Weak-lined T Tauri stars (WTTS) in and around nearby star-forming regions, including Taurus-Auriga (Neuhäuser et al. 1995a), Chamæleon (Alcalá et al. 1995) and Orion (Alcalá 1994; Sterzik et al. 1995). Spectroscopic follow-up of subsamples of these candidates finds strong Li absorption in around 60% of surveyed sources (Alcalá et al. 1995, 1996), and in some cases provides kinematic evidence that the stars newly identified from the RASS have radial velocities consistent with the previously-known WTTS population (Neuhäuser et al. 1995b). In most cases, however, such evidence is lacking, and indeed the most striking observation is the large spatial extent of the candidate WTTS, many of which lie far (10° or more) from known star-forming regions (Montmerle & Casanova 1995; Neuhäuser et al. 1995b; Sterzik et al. 1995).

The distances of the newly identified sources are mostly highly uncertain, making age determinations from the position of stars in the Hertzsprung-Russell diagram suspect.

Montmerle & Casanova (1995) quote very young ages ($\simeq 10^5$ yr) for some sources relatively close (a few degrees) to Chamæleon, while Neuhäuser et al. (1995b) give upper limits of 25 Myr for a sample of WTTS south of Taurus based on Li abundances. For a larger sample of ROSAT discovered sources, Magazzu et al. (1996) find an overabundance of Li as compared to the Pleiades for a range of spectral types, including those (eg. K and later) for which the Li width becomes important as an age indicator. These results suggest that the selection criteria for the larger samples *are* finding a new population of WTTS younger than the Pleiades, though contamination from much older (10^8 yr) stars may also be important (Hartmann, private communication), especially for the purpose of statistical studies.

Here, we note that if any significant fraction of the newly identified WTTS are young (i.e. have ages in the 1–10 Myr range common for previously known WTTS), then their origin so far from known sites of star formation poses two severe problems. Firstly, how did these sources arrive at their current location, and secondly, why is a corresponding population of dispersed *Classical* T Tauri stars not also observed. One possibility is that the number of stars forming in small isolated groups has previously been underestimated, as suggested by Feigelson (1996) on the basis of simple kinematic models for the distribution of the dispersed

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RASS stars. Alternatively, the halo sources might have been formed within known regions of star formation activity, before being ejected by dynamical interactions. In this latter scenario the number and observed distribution of the outliers implies that a reasonable fraction of all low-mass stars must be ejected from molecular clouds at relatively high velocities of several km s^{-1} or greater.

The decay of small stellar clusters has been considered as a contributor to the halo of ROSAT sources by Sterzik & Durisen (1995), and in the context of binary formation by McDonald & Clarke (1995). In these calculations decay of the cluster and ejection of most of its members occurs rapidly – within a few tens of crossing times (a few $\times 10^5$ – 10^6 yr for the McDonald & Clarke simulations, and earlier for the denser clusters modelled by Sterzik & Durisen). Although the lifetime of circumstellar discs varies widely (Strom 1995), at such early epochs most of the ejected stars would be expected to be Classical T Tauri stars (CTTS), surrounded by circumstellar discs. Since CTTS are generally well-localised in dark clouds (eg. Alcalá et al. 1995), a viable ejection model for the halo ROSAT sources requires that the ejected CTTS are converted into exclusively Weak-lined systems (where there is little or no evidence for circumstellar material) on a timescale that is short compared to the ages of the halo sources.

In this paper, we discuss the effects of an encounter leading to ejection on the accretion disc of a CTTS. The ejection of stars with velocities of a few km s^{-1} implies interactions that are close enough to severely curtail the extent of the accretion disc, but not so close as to destroy it entirely. The weakened disc will then evolve more rapidly because of the reduced viscous timescale at its outer edge, so that the rate of accretion onto the star falls rapidly. However significant K excesses could still arise from reprocessing of the stellar luminosity by a passive disc, and we show that the strength of this contribution to the spectral energy distribution depends critically on the magnetic field of the star. For weakly magnetic stars (where the disc extends to the stellar equator) the passive flux from the disc will persist long after active accretion has ceased, whereas a strong stellar field can disrupt the hot inner disc regions and reduce the reprocessing flux coincident with the decline in the mass accretion rate. Magnetic fields of the required strength have been directly detected in several WTTS (Basri, Marcy & Valenta 1992; Guenther & Emerson 1995, 1996), and many indirect lines of evidence suggest that they are common in both WTTS and CTTS (see, eg. the review by Hartmann 1994).

The plan of this paper is as follows. In Section 2, we estimate the accretion rates below which magnetic and non-magnetic systems would appear as WTTS on the basis of their near-infrared colours and $H\alpha$ equivalent width. In Section 3 we use these estimates to calculate the timescale for the CTTS \rightarrow WTTS transition, and compute the stellar densities required to eject a large number of T Tauri stars from their parent clouds. In Section 4 we verify these timescale estimates by directly computing the time-dependent evolution of the star-disc system for a typical choice of parameters. Section 5 summarizes our findings and discusses the observational consequences of the model.

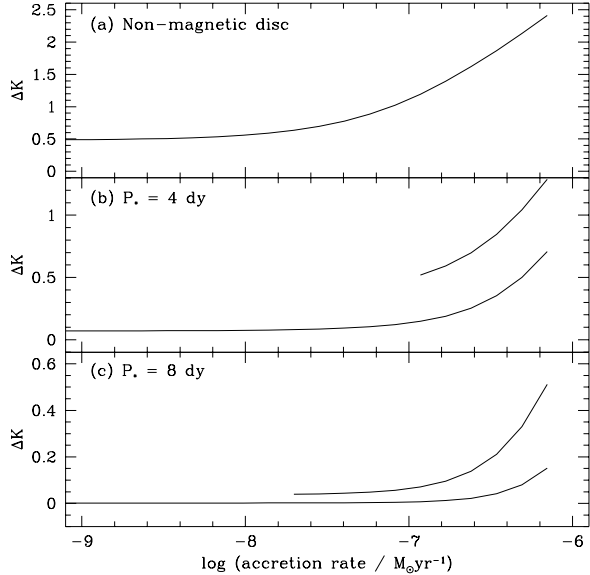


Figure 1. K excesses over the stellar photosphere for a variety of accretion disc models described in the text, as a function of the steady-state accretion rate through the disc. (a) A non-magnetic disc extending to the stellar surface. (b) A magnetically disrupted disc around a star of period $P_* = 4$ dy with $R_m = R_c$ (lower curve) and $R_m = 0.7 \times R_c$ (upper curve). (c) A magnetically disrupted disc around a star of period $P_* = 8$ dy with $R_m = R_c$ (lower curve) and $R_m = 0.7 \times R_c$ (upper curve). The curves for magnetic discs with $R_m = 0.7 \times R_c$ do not extend to very low \dot{M} , since at low accretion rates the magnetosphere must lie at larger radii.

2 MODELS FOR T TAURI ACCRETION DISCS

The parameters and mechanisms that control the transition of a star from Classical to Weak-Line status are largely unknown, but it is natural to assume that the mass accretion rate through the disc \dot{M} plays an important role. With this assumption, we define three mass fluxes; the accretion rate for a typical CTTS, \dot{M}_{CTTS} , the accretion rate below which a star appears as a WTTS in a non-magnetic model $\dot{M}_{\text{weak,noB}}$, and the corresponding quantity in a magnetospheric model $\dot{M}_{\text{weak,B}}$. A variety of observational characteristics distinguish WTTS from CTTS (see, eg. the review by Bertout 1989), but low equivalent width of $H\alpha$ ($\lesssim 10\text{\AA}$) and lack of an infra-red excess at K ($2.2\text{ }\mu\text{m}$) are common identifying features. We adopt these conditions for deciding when model systems have become WTTS, and estimate the values of $\dot{M}_{\text{weak,noB}}$ and $\dot{M}_{\text{weak,B}}$. These quantities are then used to estimate the timescale for the CTTS to WTTS conversion in magnetic and non-magnetic systems that suffer an ejection interaction.

Figure 1 shows the excess flux ΔK at $2.2\text{ }\mu\text{m}$ for a range of discs around a star of mass $1 M_\odot$ and radius $2 R_\odot$. The models include the heating of the disc from accretion, reprocessing of stellar radiation, and where appropriate work done by magnetic torques (assuming a stellar dipole field of 1 kG). The models are calculated using the formalism outlined in the Appendix. No contribution from a boundary layer or magnetically funnelled accretion shock is included as these components of the total system luminosity are not ex-

pected to be strong at K (note that in magnetospheric models the infalling material is unlikely to be optically thick at K even for $\dot{M} = \dot{M}_{\text{CTTS}}$, and will certainly have $\tau_K \ll 1$ for the lower accretion rates of interest here). For the magnetic models we have assumed that the disc is disrupted inside some magnetospheric radius R_m , which is taken either to be at corotation R_c (where the Keplerian disc has angular velocity $\Omega = \Omega_*$), or at $0.7 \times R_c$. $R_m \approx R_c$ is expected on theoretical grounds at low \dot{M} (eg Armitage & Clarke 1996; see also Wang 1996), while fitting of magnetic disc models to the spectral energy distributions of CTTS typically gives $R_m \approx 0.7 \times R_c$ (Kenyon, Yi & Hartmann 1996). Additional angular momentum loss via stellar winds (e.g. Tout & Pringle 1992) would be expected to reduce R_m below the values seen in models that assume magnetic disc linkage as the only braking mechanism. The stellar rotation rate P_* is taken to be 4 dy or 8 dy, these values being typical for WTTS and CTTS respectively (Bouvier et al. 1995).

For the non-magnetic disc model, reprocessing of the stellar luminosity ensures that an easily detectable K excess is found for all accretion rates, provided only that the disc remains optically thick at K. This will be the case down to very low accretion rates. To order of magnitude, an optical depth $\tau_K = 1$ requires a disc column density $\Sigma = 0.1 \text{ g/cm}^2$, which is at least 4 orders of magnitude below the surface density seen in CTTS disc models accreting at $10^{-7} M_\odot \text{ yr}^{-1}$. The accretion rate corresponding to $\Sigma = 0.1$ depends on the disc viscosity ν via $\dot{M} \sim 3\pi\nu\Sigma$, where ν is typically an increasing function of Σ . We conclude that $\dot{M}_{\text{weak,noB}}$ is likely to be more than 4 orders of magnitude below \dot{M}_{CTTS} , and that a disc around a non-magnetic T Tauri star would remain visible via its K excess long after significant accretion (evidenced by high equivalent width of $H\alpha$) had ceased.

For the magnetic models, the behaviour of ΔK as a function of \dot{M} is very different. If $R_m = 0.7 \times R_c$, then significant K excesses of ~ 1 mag are obtained at accretion rates of $10^{-7} M_\odot \text{ yr}^{-1}$ and above for $P_* = 4$ dy, with smaller but still readily detectable ΔK values for the longer rotation period. However, once the accretion rate has fallen sufficiently low that the magnetosphere lies at corotation, the models predict that ΔK should be low. The dependence of R_m on \dot{M} is (Clarke et al. 1995),

$$R_m = \left(\frac{2B_*^2 R_*^6}{\dot{M} \sqrt{GM_*}} \right)^{2/7}. \quad (1)$$

Thus, taking as observationally determined the result that $R_m \approx 0.7 \times R_c$ in the Classical T Tauri phase, we find that the magnetosphere should lie at corotation once $\dot{M} \lesssim 0.3 \times \dot{M}_{\text{CTTS}}$. From the Figure, we then conclude that T Tauri systems rotating at $P_* = 8$ dy would appear as WTTS on the basis of their K excess below an accretion rate of a few $\times 10^{-8} M_\odot \text{ yr}^{-1}$. For the shorter rotation period of 4 dy, ΔK falls below 0.1 magnitudes at approximately the same \dot{M} .

These results imply that judged by the near infra-red excess, a magnetic CTTS would appear indistinguishable from a WTTS at an accretion rate of $\sim 10^{-8} M_\odot \text{ yr}^{-1}$ or below. The equivalent width of $H\alpha$ in WTTS shows considerable scatter (Alcalá et al. 1993), so accretion at approximately this level probably cannot be excluded on the basis of the $H\alpha$ measurements either. Hence, we estimate that $\dot{M}_{\text{weak,B}} \sim 10^{-8} M_\odot \text{ yr}^{-1}$, and conclude that

$\dot{M}_{\text{weak,B}} \gg \dot{M}_{\text{weak,noB}}$. This critical accretion rate is then used in the following Section to estimate the timescale on which interactions leading to ejection from a cluster will reduce \dot{M} below $\dot{M}_{\text{weak,B}}$, and hence convert a CTTS to Weak-lined status.

3 TIMESCALE FOR THE CTTS \rightarrow WTTS TRANSITION

The decay of small stellar clusters has been studied by a number of authors using N-body simulations (van Albada 1968; Sterzik & Durisen 1995), and techniques that attempt to incorporate additionally the effects of discs (McDonald & Clarke 1995) or gas (Bonnell et al. 1996). Such clusters are found to dissolve within a few tens of crossing times, leading to the ejection of most of the members and the formation of one central binary. The median velocities of the escapers v_{eject} follow the scalings established for the 3-body problem,

$$\langle v_{\text{eject}} \rangle \approx 0.5 \times \left(\frac{|E_0|}{\langle m_{\text{eject}} \rangle} \right)^{1/2}, \quad (2)$$

where m_{eject} are the masses of the ejected stars, and $|E_0| \propto M_c^2/R_c$ is the total energy of the system with mass M_c and scale length R_c (Valtonen & Mikkola 1992; Sterzik & Durisen 1995). For a small cluster containing N stars of mass M_* , the above expression implies,

$$R_c \sim 10^3 \text{ a.u.} \times \left(\frac{N}{10} \right) \left(\frac{M_*}{M_\odot} \right) \left(\frac{v_{\text{eject}}}{5 \text{ km/s}} \right). \quad (3)$$

This broadly agrees with the numerical results suggesting that stellar separations in the 300-1000 a.u. range are required to generate significant numbers of escapers with v_{eject} greater than a few kms^{-1} . The required clusters are thus vastly denser than the stellar density in regions such as Taurus-Auriga, even when account is given to the observed degree of subclustering (Gomez et al. 1993). However such clusters are also short lived, typically $< 10^5 \text{ yr}$ (Sterzik & Durisen 1995), and hence the observed state of Taurus *cannot* necessarily be taken as evidence that stars were not born in much more compact groups. Indeed the dissolution of such initial clusters might plausibly lead within a few Myr to *both* high velocity escapers and dilute aggregates (composed of stars ejected at only $\sim \text{a kms}^{-1}$) similar to those observed by Gomez et al. (1993). Detailed population synthesis would be required to address this possibility in a more quantitative fashion. As discussed by McDonald & Clarke (1995) and Sterzik & Durisen (1995), the formation of stars within such transitory clusters is consistent both with some theoretical models of star formation (Boss 1993), and the observed high fraction of binaries in the pre-main-sequence (eg. Ghez 1996).

For a dynamical ejection model to be relevant to the formation of the RASS halo of WTTS, v_{eject} must be a few kms^{-1} or greater. Here we assume that conditions in the initial stellar clusters are conducive to producing such velocities (i.e. similar to those used as initial conditions by Sterzik & Durisen 1995), and calculate the effects of those ejections on circumstellar discs.

To relate v_{eject} to the distance of closest approach in the encounter that led to the ejection, R_{peri} , we make use of prior work on the scattering of single stars by binaries

(for details see, e.g. Davies 1995). The energy lost from the binary ΔE is related to the binding energy of the binary, E_{bin} , via

$$\Delta E \lesssim 0.4 \times E_{\text{bin}} = 0.4 \times \frac{GM^2}{2d_{\text{bin}}}, \quad (4)$$

where d_{bin} is the separation of the binary before the encounter. Making use of the further result that $d_{\text{bin}} \approx R_{\text{peri}}$, we find

$$v_{\text{eject}} \approx 15 \text{ km/s} \times \left(\frac{R_{\text{peri}}}{1 \text{ a.u.}} \right)^{-1/2}, \quad (5)$$

for stars of solar mass. Ejection velocities of $v_{\text{eject}} = 3 - 10 \text{ km/s}$, then imply $R_{\text{peri}} \sim 2 - 25 \text{ a.u.}$ Star-disc encounters have been extensively modelled (Hall, Clarke & Pringle 1996; Clarke & Pringle 1993), and these simulations suggest that the accretion disc following the encounter has an outer edge at $\sim R_{\text{peri}}/2$. The ejected stars would thus be expected to harbour remnant discs with outer radii $R_{\text{out}} \lesssim 10 \text{ a.u.}$ immediately following the interaction.

The weakened disc will then evolve *faster* as a consequence of the reduced viscous timescale t_ν at R_{out} . The viscous timescale is given by (e.g. Pringle 1981),

$$t_\nu \sim \frac{1}{\alpha} \left(\frac{R}{H} \right)^2, \quad (6)$$

where α is the Shakura-Sunyaev viscosity parameter, H is the disc scale height, and all quantities are evaluated at radius R . For stars of solar mass,

$$t_\nu \sim 1.6 \times 10^4 \text{ yr} \left(\frac{\alpha}{10^{-3}} \right)^{-1} \left(\frac{(H/R)_{R_{\text{out}}}}{0.1} \right)^{-2} \left(\frac{R_{\text{out}}}{1 \text{ a.u.}} \right)^{3/2}, \quad (7)$$

where α is the Shakura-Sunyaev viscosity parameter appropriate to the outer regions of the disc following the interaction.

Thus provided that $\alpha_{R_{\text{out}}} \gtrsim 10^{-3}$ (as is likely since even $\alpha = 10^{-3}$ implies worryingly large disc masses at radii of several a.u.) and $(H/R) \gtrsim 0.1$, the viscous timescale of the truncated disc will be short compared to the typical disc lifetime in CTTS. For example at 5 a.u., which corresponds to the outer edge of the disc in a star ejected at 5 kms^{-1} , $t_\nu \sim 2 \times 10^5 \text{ yr}$ with the fiducial parameters given above. The same conclusion follows by noting that unless α or (H/R) are strongly increasing functions of R in the outer regions of the disc, the radial dependence of t_ν is approximately as $\Omega^{-1} \propto R^{3/2}$. A typical T Tauri disc has a lifetime of a few Myr, which implies $t_\nu \sim 1 \text{ Myr}$. Reducing R_{out} by a modest factor of ~ 5 then ensures that immediately following an encounter (before the disc has had time to expand viscously) the viscous timescale will be reduced by around an order of magnitude. Estimates of T Tauri disc sizes are generally $\sim 10^2 \text{ a.u.}$ or greater (McCaughrean & O'Dell 1996), and hence encounters at radii of $\sim 10 \text{ a.u.}$ are likely to meet this condition.

The viscous timescale can be regarded as a characteristic time for the decay of the disc surface density and accretion rate. As $\dot{M}_{\text{CTTS}} \approx 10^{-7} M_\odot \text{ yr}^{-1}$, only a few viscous times will be required before \dot{M} through the truncated disc falls below $\dot{M}_{\text{weak,B}}$. Thus within a few times t_ν (equation 7), the initially Classical T Tauri star will lose the ΔK and $H\alpha$ signatures of a CTTS, and will appear as a Weak-Lined system. In this model circumstellar material will still exist

around the star for a further, perhaps lengthy, period, but the low accretion rate and the hole created by the stellar magnetosphere renders it undetectable in the near infra-red.

We emphasise that the same conclusion does *not* follow for non-magnetic disc models. In this scenario, the interaction reduces t_ν exactly as for the magnetic case, but a large number of viscous times are still necessary before \dot{M} falls below $\dot{M}_{\text{weak,noB}}$. Before the accretion rate falls this low, the disc will have had time to re-expand to its original extent, restoring t_ν to a much larger value. As a consequence, the reduction in the duration of the CTTS phase will be much less marked, and we would expect the ejected systems to display infra-red excesses from passive discs without significant active accretion.

4 NUMERICAL SIMULATIONS

To verify the estimates derived in Section 2, we have calculated explicitly the evolution of the coupled star-disc system following an encounter that destroys the outer accretion disc. The response of the disc to magnetic and viscous torques is described using the evolution equation given by Livio & Pringle (1992),

$$\begin{aligned} \frac{\partial \Sigma}{\partial t} = & \frac{3}{R} \frac{\partial}{\partial R} \left[R^{1/2} \frac{\partial}{\partial R} (\nu \Sigma R^{1/2}) \right] \\ & + \frac{1}{R} \frac{\partial}{\partial R} \left(\frac{\Omega - \Omega_*}{\Omega} \frac{B_z^2 R^{5/2}}{\pi \sqrt{GM_*}} \right), \end{aligned} \quad (8)$$

which we solve together with equations for the spin period and magnetic field of the star. The stellar model used is a $0.9985 M_\odot$ model calculated using the most recent version of the Eggleton code (Pols et al. 1995), as modified for pre-main-sequence evolution by Tout (private communication). The model and numerical details are described elsewhere (Armitage & Clarke 1996).

Figure 2 shows the time-dependence of the disc mass, accretion rate, stellar spin period and K excess for two models; one in which the disc beyond 5 a.u. is lost at $t = 2 \times 10^5 \text{ yr}$ (representing the effect of an ejection interaction), and a ‘control’ model in which the disc evolves undisturbed. We also show the evolution of ΔK for a non-magnetic model subject to the same disruptive encounter. The main parameters of the simulations are; an outer boundary condition of $\Sigma = 0$ at 50 a.u., a stellar magnetic field $B_* = 1500 \text{ G} \times (P_*/4 \text{ dy})$, an initial disc mass of $0.3 M_\odot$, and an initial accretion rate of $1.5 \times 10^{-7} M_\odot \text{ yr}^{-1}$. The viscosity prescription assumes an α in the inner disc of 10^{-3} , and gives an evolutionary timescale for the unperturbed disc of $\sim 10^6 \text{ yr}$, consistent with the inferred lifetime of CTTS discs (Simon & Prato 1995). The K excess ΔK is calculated using identical models to those of the previous Section, except that the assumption that the disc is in a steady state is relaxed and we use instead the computed surface density to obtain the active accretion component.

Following the encounter, the accretion rate drops rapidly, reflecting the reduced viscous timescale at the new outer edge (t_ν decreases by a factor ~ 10 following the interaction). At late times, when the weakened disc has re-expanded to its previous size, the accretion rate is a factor of ~ 6 times lower than in the model that evolves undisturbed, or approximately $(1-2) \times 10^{-9} M_\odot \text{ yr}^{-1}$ at $t = 2 \text{ Myr}$

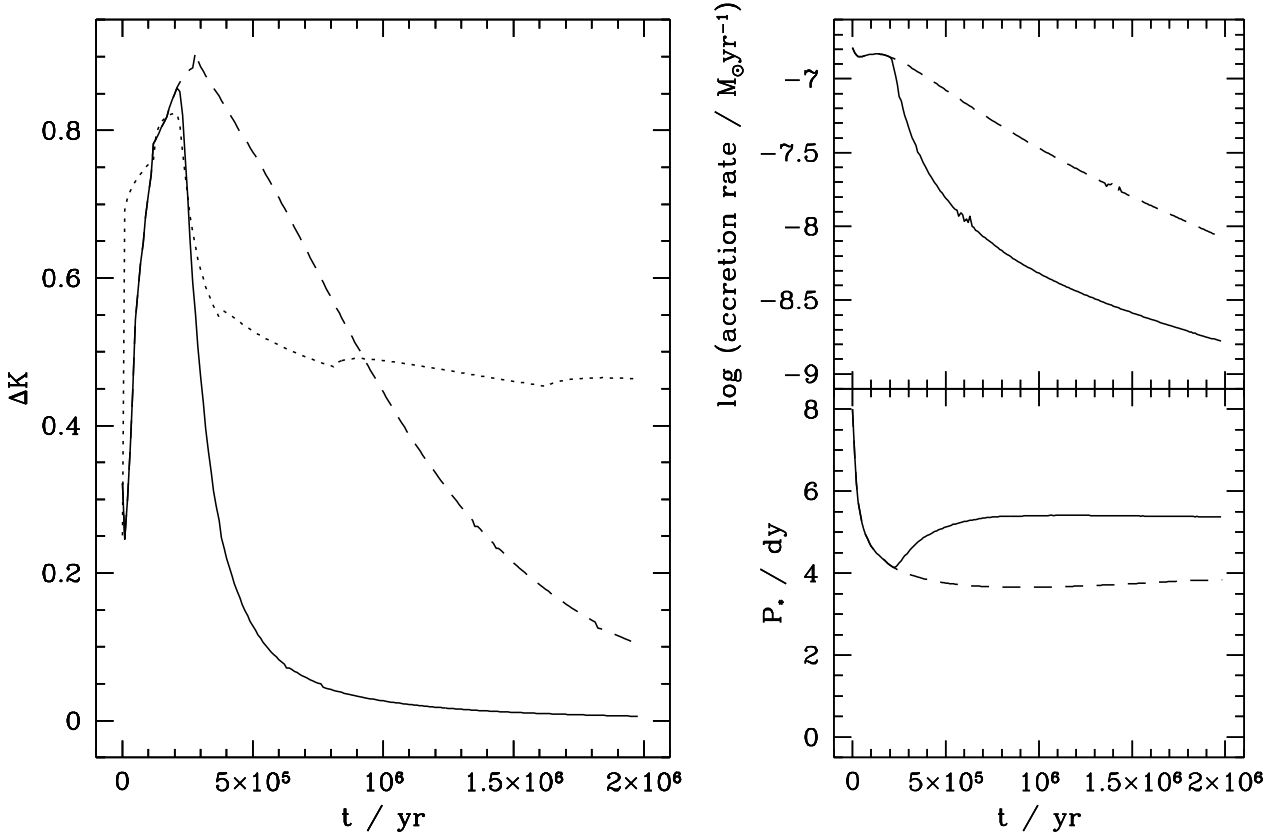


Figure 2. Comparison of the evolution of an undisturbed star-disc system (dashed line) with one experiencing an encounter at $t = 2 \times 10^5$ yr that removes all mass outward of 5 a.u. (solid curve). Both models assume a disc disrupted at small radii by a stellar magnetosphere. The panels show the time-dependence of the monochromatic flux excess ΔK at $2.2 \mu\text{m}$, accretion rate, and stellar spin period. The K excess for a non-magnetic system undergoing the same encounter as the magnetic model is also shown (dotted line).

for these models. The rotation period of the ‘ejected’ star is marginally increased as compared to the control model, because the spin-up torque from accretion is reduced while the spin-down torque from magnetic braking is unaffected. The K excess drops rapidly due to a combination of lower \dot{M} , increased ratio of R_m/R_c (which is ~ 1 in the weakened disc simulation), and increased R_c due to the slower rotation. ΔK falls below 0.1 magnitudes within 0.5 Myr, and is negligible at the end of the simulation. This reduction in ΔK as compared to the control run (which is itself still magnetically disrupted at small R) amounts to a factor of ~ 10 , in agreement with the estimates presented previously. The run in which a non-magnetic disc is subjected to an encounter also follows the expected behaviour. Immediately after the interaction, ΔK drops as for the magnetic case due to the reduced \dot{M} . However, at late times the K excess remains strong due to the reprocessing luminosity of the undisturbed disc at small radii.

The extent to which the length of the CTTS phase is reduced by encounters is shown as Figure 3. A series of calculations with the parameters given above were run, varying only the outer radius at which the disc was truncated by the interaction. The time subsequent to the interaction required for \dot{M} to fall to $10^{-8} M_\odot \text{yr}^{-1}$ is plotted as a function of

v_{eject} , which is related to R_{peri} via equation (5). Also plotted is the time required for ΔK to fall below 0.1 magnitudes.

From the Figure, it can be seen that encounters that produce high velocity escapers lead to a rapid decline in \dot{M} and ΔK on a timescale of at most a few $\times 10^5$ yr. The most destructive encounters considered here (at 10 km s^{-1}) reduce the accretion rate by an order of magnitude in 10^5 yr. At lower velocities ($v_{\text{eject}} \approx 2 \text{ km s}^{-1}$), the influence of the interactions tapers off as the mass and viscous time of the remnant disc approach the values of the undisturbed system. For the viscosity and initial conditions (primarily, the choice of initial disc mass) used here, this occurs at $v_{\text{eject}} \lesssim 2 \text{ km s}^{-1}$.

The form of the curves shown in Figure 3 reflects the relationship between the viscous timescale of the undisturbed disc and that of the truncated disc following the encounter (equation 7). There are little in the way of observational constraints on the disc viscosity at large radius (essentially, just the disc lifetime which is expected to be $\mathcal{O}(t_\nu)$ for the disc), and thus there is bound to be considerable uncertainty inherent in these timescale estimates. Nonetheless, the results presented here indicate that encounters close enough to eject stars at velocities, $v_{\text{eject}} \gtrsim 5 \text{ km s}^{-1}$, should be disruptive enough of the disc to rapidly cut-off accretion, and, if the star possesses a magnetosphere extending to a few stel-

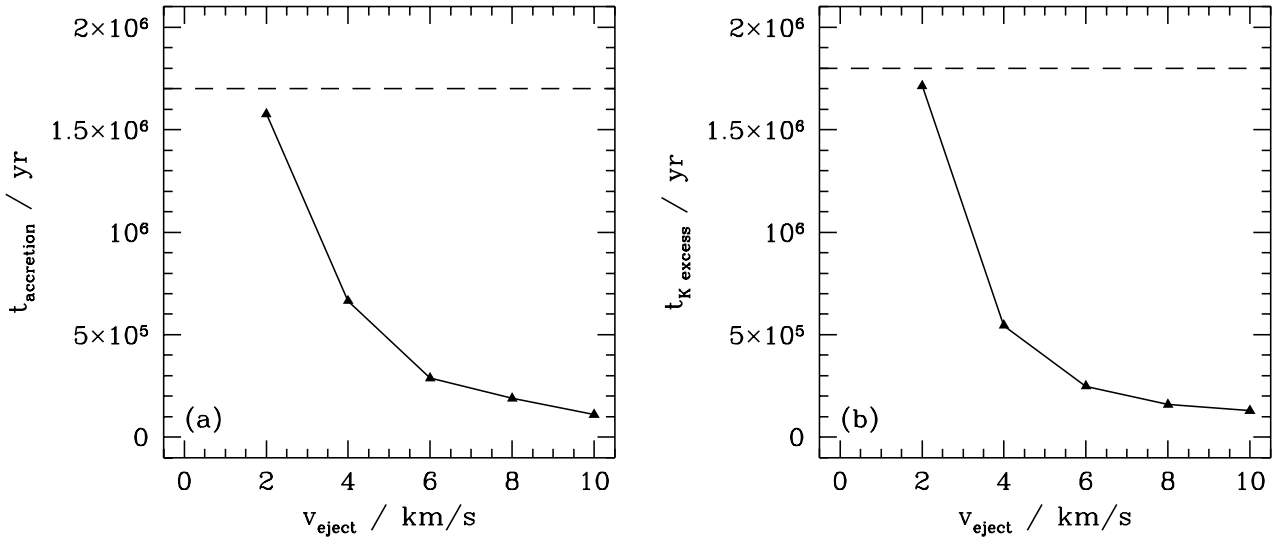


Figure 3. Effect of the encounter on the accretion rate and K excess, as a function of the ejection velocity v_{eject} (or, equivalently, the periastron separation). (a) Time after encounter required for the accretion rate to fall below $10^{-8} M_{\odot} \text{yr}^{-1}$. (b) Time required for the K excess to drop below 0.1 magnitudes. In both panels the period required for the undisturbed disc model to reach these limits is shown as a dashed line.

lar radii, additionally lead to a sharp drop in the near-IR excess. These high velocities are required if any significant fraction of the most dispersed RASS sources are relatively young (< 10 Myr) and originated as escapers from known molecular clouds (Sterzik et al 1995). Less destructive encounters, with periastron separations of 20-30 a.u. and ejection velocities of $\sim 3 \text{ km s}^{-1}$, are predicted to reduce the CTTS phase by modest factors of around 2.

5 SUMMARY

In this paper, we have investigated the evolution of discs around Classical T Tauri stars which are subjected to disruptive encounters within the environment of small clusters. We find that interactions that are able to eject stars from the cluster at velocities of a few km s^{-1} or greater lead to truncation of the accretion disc, and greatly accelerate its evolution. The rate of accretion through the disc drops rapidly for several viscous times of the remnant disc, and falls to very low levels within, typically, a few $\times 10^5$ yr. Since ejections at these velocities from small clusters happen at an early epoch, the curtailment of further infall onto the outer regions of discs in escaping stars would also tend to reduce the accretion rate at later times.

The further evolution of the discs in ejected systems then depends on the strength of the stellar magnetic field. For systems with weak magnetic fields, we predict a period in which a passive reprocessing disc generates prominent infra-red excesses at all wavelengths. Alternatively, for stars with a strong, ordered, magnetic field, the stellar magnetosphere should rapidly disrupt the inner regions of the disc out to close to the corotation radius. As magnetic fields of

the required strength are inferred from other observations, we regard this magnetic scenario as the more probable. Observationally such systems would show negligible infra-red excesses at K , but would still possess infra-red emission at wavelengths $\lambda \gtrsim 5 \mu\text{m}$. Such transition systems would have stellar rotation periods comparable to the Classical T Tauri stars, and detectable emission at mm wavelengths that is, however, depleted by the reduction of the disc mass as a result of the encounter.

In the context of models wherein the Li-rich halo RASS sources originate as escapers from young clusters (Sterzik & Durisen 1995), the present study implies that the lack of a dispersed CTTS population is not a problem, even if some fraction of the dispersed WTTS turn out to be young (~ 1 Myr). The interactions leading to ejection at such high velocities necessarily cut-off accretion within less than this time. However there should be systems (preferentially the younger ones), where residual circumstellar material exists, and this may be detectable at longer infra-red and mm wavelengths. Measurements of the proper motions and determinations of the ages of these RASS sources should provide a decisive test of such scenarios.

This model, in common with previous work (Clarke et al. 1995), predicts stars with properties intermediate between Classical and Weak-Lined T Tauri systems. In particular, if the disc is cleared at the end of the CTTS phase ‘inside-out’, for example by winds or a stellar magnetosphere, it is hard to avoid a period in which the system is ‘weak’ on small scales but ‘strong’ on large scales. Such systems should have detectable mid infra-red and mm fluxes without corresponding K or $H\alpha$ emission. If such systems are not observed, that would be strong evidence in favour either of an unexpectedly short disc clearing timescale, or

of disc dissipation via processes unconnected to the central star.

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REFERENCES

- Adams F.C., Shu F.H., 1986, *ApJ*, 308, 836
 Alcalá J.M., Covino E., Franchini M., Krautter J., Terranegra L., Wichmann R., 1993, *A&A*, 272, 225
 Alcalá J.M., 1994, Ph.D. Thesis, Ruprecht-Karls-Universität, Heidelberg
 Alcalá J.M., Krautter J., Schmitt J.H.M.M., Covino E., Wichmann R., Mundt R., 1995, *A&ASS*, 114, 109
 Alcalá J.M. et al, 1996, *A&A*, in press
 Armitage P.J., Clarke C.J., 1996, *MNRAS*, 280, 458
 Basri G., Marcy G.W., Valenti J.A., 1992, *ApJ*, 390, 622
 Bonnell I.A., Bate M., Clarke C.J., Pringle J.E., 1996, *MNRAS*, submitted
 Boss A.P., 1993, *ApJ*, 410, 157
 Bouvier J., Covino E., Kovo O., Martin E.L., Matthews J.M., Terranegra L., Beck S.C., 1995, *A&A*, 299, 89
 Clarke C.J., Armitage P.J., Smith K.W., Pringle J.E., 1995, *MNRAS*, 273, 639
 Clarke C.J., Pringle J.E., 1993, *MNRAS*, 261, 190
 Davies M.B., 1995, *MNRAS*, 276, 887
 Feigelson E.D., 1996, *ApJ*, in press
 Ghez A.M., 1996, in *Evolutionary Processes in Binary Stars*, eds. R.A.M.J. Wijers, M.B. Davies & C.A. Tout, Kluwer Academic Publishers, p. 1
 Gomez M., Hartmann L., Kenyon S.J., Hewett R., 1993, *AJ*, 105, 1927
 Guenther E.W., Emerson J.P., 1995, in *Siebenmorgen R., Käuff H.U.*, eds, *ESO Proceedings, The role of dust in the formation of stars*, in press
 Guenther E.W., Emerson J.P., 1996, *A&A*, 309, 777
 Hall S.M., Clarke C.J., Pringle J.E., 1996, *MNRAS*, 278, 303
 Hartmann L., 1994, in *Duschl W.J., Frank J., Meyer F., Meyer-Hofmeister E., Tscharnuter W.M.*, eds, *NATO ASI Series C417, Theory of Accretion Disks-2*. Kluwer Academic Publishers, Dordrecht, p. 19
 Kenyon S.J., Hartmann L., 1987, *ApJ*, 323, 714
 Kenyon S.J., Yi I., Hartmann L., 1996, *ApJ*, 462, 439
 Livio M., Pringle J.E., 1992, *MNRAS*, 259, 23P
 Magazzu et al., 1996, *A&A*, submitted
 McCaughrean M.J., O'Dell C.R., 1996, *AJ*, 111, 1977
 McDonald J.M., Clarke C.J., 1995, *MNRAS*, 275, 671
 Montmerle T., Casanova S., 1995, *Rev. Mex. As. Ap. (Conference Series)*, 1, 329
 Neuhauser R., Sterzik M.F., Schmitt J.H.M.M., Wichmann R., Krautter J., 1995, *A&A*, 295, L5 (1995a)
 Neuhauser R., Sterzik M.F., Torres G., Martin E.L., 1995, *A&A*, 299, L13 (1995b)
 Pols O., Tout C.A., Eggleton P.P., Han Z.W., 1996, *MNRAS*, 274, 964
 Pringle J.E., 1981, *ARA&A*, 19, 137
 Simon M., Prato L., 1995, *ApJ*, 450, 824
 Sterzik M.F., Alcalá J.M., Neuhauser R., Schmitt J.H.M.M., 1995, *A&A*, 297, 418

- Sterzik M.F., Durisen R.H., 1995, *A&A*, 304, L9
 Strom S.E., 1995, *Rev. Mex. As. Ap. (Conference Series)*, 1, 317
 Tout C.A., Pringle J.E., 1992, *MNRAS*, 256, 269
 Valtonen M., Mikkola S., 1991, *ARAA*, 29, 9
 van Albada T.S., 1968, *Bull. Astron. Inst. Neth.*, 19, 479
 Wang Y.-M., 1996, *ApJ*, 465, L111

APPENDIX: CALCULATING DISC SPECTRAL ENERGY DISTRIBUTIONS

The spectral energy distributions for the magnetic disc models are calculated assuming that annuli in the disc radiate as blackbodies with effective temperature T_e , where

$$T_e^4 = T_\nu^4 + T_p^4 + T_B^4, \quad (9)$$

and the terms on the right-hand side represent respectively the contributions from active accretion, reprocessing of the stellar luminosity, and work done on the disc by the magnetic field. For a disc in which the energy from viscous dissipation is radiated locally

$$2\sigma T_\nu^4 = \frac{9}{4}\nu\Sigma\Omega^2, \quad (10)$$

where σ is the Stefan-Boltzmann constant. Evaluation of the right-hand side of this expression does not require knowledge of the specific form of ν , but for a magnetic disc model it does depend on the assumed magnetic field configuration. In Section 2 we compute $\nu\Sigma$ from the steady-state solution of the disc evolution equation (8) with boundary conditions $\nu\Sigma = 0$ at $R = R_m$ and $\nu\Sigma = \dot{M}/(3\pi)$ at large radius (the standard non-magnetic disc expression), yielding

$$\nu\Sigma = \frac{\dot{M}}{3\pi} \left(1 - \sqrt{\frac{R_m}{R}} \right) - \beta R^{-7/2} \left(\left(\frac{R}{R_m} \right)^3 - 1 \right) + 2\beta R_c^{-3/2} R^{-2} \left(\left(\frac{R}{R_m} \right)^{3/2} - 1 \right), \quad (11)$$

with $\beta = (B_* R_*^3)^2 / (9\pi \sqrt{GM_*})$. The main assumption required to derive this expression is in the form of the radial dependence of the magnetic torque, and is described in detail in a previous paper (Armitage & Clarke 1996). Note that this solution is not in general physically reasonable ($\nu\Sigma > 0$) for all choices of R_m , reflecting the fact that for large B_* and/or small \dot{M} steady solutions with $R_m \ll R_c$ do not exist. In Section 3 we use $\nu\Sigma$ calculated directly from the time-dependent solution of equation (8).

For the component due to reprocessing of stellar radiation, we utilise the results of Kenyon & Hartmann (1987) and Adams & Shu (1986). These authors obtain

$$T_p^4 = \frac{T_*^4}{\pi} \left(\sin^{-1} \left(\frac{R_*}{R} \right) - \left(\frac{R_*}{R} \right) \sqrt{1 - \left(\frac{R_*}{R} \right)^2} \right), \quad (12)$$

for the case assumed here of a flat reprocessing disc.

The magnetic torques arising from field lines linking the star and the disc will also do work on the disc material, and some fraction of this may be thermalized and heat the disc material. Assuming *all* the available energy goes into heating the disc,

$$2\sigma T_B^4 = (B_* R_*^3)^2 |\Omega - \Omega_*| R^{-5}. \quad (13)$$

The actual fraction of the available energy that goes into reheating the disc material is uncertain, and so for the purposes of this work we adopt the conservative option of choosing the maximum value. Even then, this term is typically smaller than T_p , and so the uncertainty in its value does not seriously change the estimate of the disc temperature at low accretion rates.